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TENSILE PROPERTIES OF 6A1-4V TITANIUM-ALLOY SHEET UNDER RAPID-HEATING AND CONSTANT-TEMPERATURE CONDITIONS

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TENSILE PROPERTIES OF 6Al-4V TITANIUM-ALLOY SHEET UNDER RAPID-HEATING AND CONSTANT-TEMPERATURE CONDITIONS

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SUMMARY

Results are presented of rapid-heating tests conducted to determine the tensile strength of 6Al-4V titanium-alloy sheet heated to failure at uniform temperature rates from 0.2° F to 100° F per second under constant-load conditions. Yield strength and rupture strength, obtained from rapid-heating tests, are compared with yield and tensile strengths of elevated-temperature tensile stress-strain tests of 1/2-hour exposure. Minimum creep rate and stress-time-deformation curves for tensile creep tests are presented. The applicability of master curves and temperature-rate parameters to the prediction of yield and rupture temperatures under rapid-heating conditions is investigated. The activation energy for creep is determined, and a comparison is made between yield temperatures under rapid-heating conditions and the yield temperatures calculated from a phenomenological relation between stress, strain rate, and temperature.

INTRODUCTION

Aerodynamic heating of aircraft and missiles has led to considerable research on the effect of rapid heating on the tensile strength of materials. These investigations have shown that the strength depends upon the temperature rate and can be considerably higher for rapid-heating conditions than for constant-temperature conditions.

The investigations at the Langley Research Center to determine the tensile strength of various sheet materials under rapid-heating and constant-load conditions are briefly summarized in reference 1. The materials included in the program are 7075-T6 and 2024-T3 aluminum alloys (ref. 2), Inconel and RS-120 titanium alloy (ref. 3), HK31XA-H24 and AZ31A-O magnesium alloys (refs. 4 and 5, respectively), and Inconel X (ref. 6).

This paper presents the results of rapid-heating tests of 6Al-4V titanium-alloy sheet heated to failure under constant-tensile-load conditions. Temperature rates varied from about 0.2° F to 100° F per second. The results of these tests are compared with those of the conventional elevated-temperature tensile stress-strain tests. The application of a master curve for the prediction of yield and rupture temperatures is investigated. Yield temperatures determined experimentally are compared with those calculated by a solution of a phenomenological relation given in reference 7. The results of tensile creep tests, required for the application of the relation, are also presented.

SYMBOLS

R	gas constant, taken as 2 cal per mole per °K
s	constant, per hr per °K
T	temperature, °K unless otherwise specified
$\dot{T}$	temperature rate, °K per hr unless otherwise specified
T_y	yield temperature, °K unless otherwise specified
ΔH	activation energy for creep, cal per mole
σ	applied stress, ksi
σ_o	stress constant, ksi

TEST SPECIMENS AND PROCEDURE

Material and Specimens

The 6Al-4V titanium-alloy sheet was received in the heat-treated condition. The sheet had been solution treated at 1,700° F for 20 minutes and aged at 1,000° F for 4 hours. The chemical composition and the room-temperature longitudinal tensile properties of the 0.125-inch-thick sheet, as given by the supplier, are shown in table 1.

The rapid-heating specimens, tensile stress-strain specimens, and tensile creep specimens (fig. 1) were cut from the sheet with the longitudinal axis of the specimen parallel to the rolling direction of the sheet. Two tensile stress-strain specimens were cut with the longitudinal axis perpendicular to the rolling direction in order to obtain some information on the properties in the transverse direction.

Test Procedure

Conventional elevated-temperature tensile stress-strain tests were conducted as described in reference 8. The specimens were exposed to the test temperature for 1/2 hour before loading at a constant strain rate of 0.002 per minute. Specimen temperatures were measured with two thermocouples of No. 30 (American wire gage) chromel-alumel wire, clamped to opposite sides of the specimen at the midpoint.

In the rapid-heating tests, the specimen was first loaded to the desired stress level by a deadweight loading system and then heated at a constant temperature rate until failure occurred. A general view of the equipment used in the rapid-heating tests is shown in figure 2. Heating was accomplished by passing an electric current directly through the specimen. Strains were measured over a one-inch gage length by two linear variable differential transformer gages connected to the specimen through lever arms and gage frames. (See fig. 1 of ref. 1.) The specimen temperatures were measured with two thermocouples of No. 30 (American wire gage) chromel-alumel wire which were spotwelded to the midpoint of the specimen by a controlled-condenser-discharge spotwelder.

Tensile creep tests were conducted at elevated temperatures. In these tests the specimens were exposed for 1/2 hour to the test temperature, then loaded, and allowed to creep under constant-load conditions until rupture occurred. Strain and temperature were measured as in the tensile stress-strain tests.

RESULTS AND DISCUSSION

Stress-Strain Tests

The elevated-temperature tensile properties of 6Al-4V titanium-alloy sheet, exposed 1/2 hour to the test temperature and then loaded at a strain rate of 0.002 per minute, are given in table 2 and illustrated in figures 3, 4, and 5.

Representative stress-strain curves at temperatures up to 1,200° F are shown in figure 3. The results are presented in a carpet plot to facilitate interpolation. The yield strength and tensile strength as a function of temperature are shown in figure 4, and the change of elastic modulus with temperature is shown in figure 5.

From room temperature up to about 800° F (fig. 3), the strain at yield has an approximately constant value. Above about 800° F (fig. 4) the yield strength and the tensile strength drop sharply. Young's modulus (fig. 5) decreases rapidly with temperature above 800° F.

Rapid-Heating Tests

The results of rapid-heating tests of the material are given in table 3 and illustrated in figures 6 to 9. The thermal-expansion curve, determined at zero stress, is shown in figure 6 and the average coefficients of linear thermal expansion, obtained from that curve, are listed in table 4.

Representative strain-temperature curves at four stress levels for temperature rates from 0.2° F to 100° F per second are shown in figure 6. Each curve represents a single test, the experimental curves having been fitted to the calculated thermal-elastic curves. At the lower temperatures, before plastic deformation occurs, all the test results for a given stress follow a single curve, which is the sum of the elastic and thermal strains. This curve can be calculated inasmuch as the thermal-expansion (table 4) and elastic-modulus (fig. 5) values are known. At the higher temperatures, plastic deformation occurs as shown by the experimental curves turning upward from the thermal-elastic curves. For a given stress the specimen heated at the lowest temperature rate began to yield first. Yield temperatures, defined as temperatures at which a plastic strain of 0.2 percent occurs, are determined at an offset of 0.2 percent from the calculated thermal-elastic curve, as indicated by the tick marks.

The variation of the yield and rupture temperatures with temperature rate plotted on a logarithmic scale is shown in figure 7 by the solid curves. The additional curves of figure 7 are discussed in subsequent sections. Both yield and rupture temperatures increase with temperature rate and/or with decreasing applied stress. If experimental scatter is neglected, the relationship between yield and rupture temperatures and the logarithm of the temperature rate tends to be linear at each stress level. Rupture temperatures (fig. 7(b)) exhibit considerably more scatter than yield temperatures (fig. 7(a)) and show a greater increase with temperature rate than do the yield temperatures.

Comparisons of the results of the rapid-heating and the stress-strain tests are shown in figures 8 and 9. The rapid-heating results (dashed curves) were obtained from a cross plot of the experimental curves of figure 7; the stress-strain data are taken from figure 4. In contrast with tests of some other alloys (for example, ref. 2), the stress-strain test of 6Al-4V titanium alloy indicates a higher yield strength in the lower temperature region (below about 800° F). For a temperature rate of 100° F per second and temperatures above 800° F, the yield strength (fig. 8) is appreciably greater (at $1,200^{\circ}$ F almost three times greater) than the yield strength obtained from the stress-strain test. The comparison (fig. 9) of tensile strength as determined by stress-strain tests with rupture strength as determined by rapid-heating tests shows the marked effect that rapid heating has on the rupture strength.

Rupture strength decreases almost linearly with temperature in the temperature range in which data are available.

Creep Tests

The results of nine tensile creep tests at 800° F and 1,000° F are shown in table 5 and illustrated in figure 10. In figure 10(a), the stress is plotted against the minimum creep rate on a logarithmic scale. Although the data points are scattered at both temperatures, almost parallel straight lines can be fitted to the points. Such parallelism is necessary for the application of the phenomenological relation between stress, strain rate, and temperature given in reference 7. The change in temperature has a marked effect on the minimum creep rate, as indicated by the displacement of the curves. The stress-time curves for a creep strain of 0.2, 0.5, and 1.0 percent and for rupture at 800° F and 1,000° F are shown in figure 10(b). Except for a few points the data fall on fairly straight lines. Three creep tests were conducted at 600° F. It was necessary at this temperature to load the specimen well above the yield stress before any appreciable creep was obtained. It was obvious that this material is highly creep resistant at 600° F.

APPLICATION OF A TEMPERATURE-RATE PARAMETER

The master curves using a temperature-rate parameter for yield strength and rupture strength are shown in figure 11. The determination of these curves is described in reference 2. The parameter, with the constants determined for this alloy, takes the form

$$\frac{T - 300}{7.5 + \log_{10} \dot{T}} \qquad (1)$$

where T is either the yield or rupture temperature in °F and $\dot{T}$ is the temperature rate in °F per second. For the yield strength and rupture strength correlation between the data and the master curve is fair at all stresses. Yield and rupture temperatures were obtained from the master curve and are compared with the experimental data in figure 7. For the yield temperatures the agreement is excellent at 50 ksi and good at the other stress levels. For the rupture temperatures agreement is again best at 50 ksi but generally not as good as the agreement for the yield temperatures.

APPLICATION OF A PHENOMENOLOGICAL RELATION

Yield temperatures under rapid-heating and constant-load conditions were calculated by means of a solution of a phenomenological relation (ref. 7). The results of these calculations are illustrated in figures 7(a) and 8. This relation has previously been applied to low-carbon steel, 7075-T6 aluminum alloy, and Inconel X (refs. 1, 7, and 9).

Yield temperatures, at which 0.2-percent plastic strain occurs, were calculated from a solution of the relation, given in reference 9, which is

L331

$$\log_e f\left(\frac{\Delta H}{RT_y}\right) = \log_e\left[\frac{\dot{T}}{s(\Delta H/R)^2}\right] - \frac{\sigma}{\sigma_o} - 6.2 \qquad (2)$$

where

$$f\left(\frac{\Delta H}{RT_y}\right) = \exp\left(-\frac{\Delta H}{RT_y}\right)\left(\frac{\Delta H}{RT_y}\right)^{-3}\left(1 - \frac{3}{\Delta H/RT_y} + \ldots\right)$$

For a given stress σ and a given temperature rate $\dot{T}$, the yield temperature T_y can be determined if ΔH, s, and σ_o are known. These constants were determined from the tensile creep data. Their values were as follows:

$$\Delta H = 70{,}700 \text{ cal/mol}$$

$$\sigma_o = 8.56 \text{ ksi}$$

$$s = 5.71 \times 10^{11} \frac{1}{\text{hr}/^{\circ}\text{K}}$$

The computed and experimental yield temperatures are compared in figure 7(a). There is good agreement between yield temperatures obtained by use of equation (2) and those obtained by experiment at the highest temperatures, fair agreement at the intermediate temperatures, and no agreement at the lowest temperatures. The computed and experimental yield strengths obtained from a cross plot of figure 7(a) are compared in figure 8. In the low temperature region equation (2) predicts yield strengths which are much higher than those determined experimentally. However, agreement between the computed values and experimental values improves in the high temperature region.

There are two possible reasons for the lack of agreement at low temperatures. First, in reference 7 it is stated that creep behavior of metals differs at high and at low temperatures. Furthermore, reference 10 shows that the activation energy for creep is fairly constant above a certain temperature. This temperature is about 45 percent of the absolute melting temperature for a metal but it may vary considerably for an alloy. Since the phenomenological relation (ref. 7) requires a single mechanism for creep and a constant activation energy, it is unlikely that good agreement would be obtained at low temperatures. The second reason for lack of agreement is the possible error in determining the constants which were based on a limited number of creep tests.

CONCLUDING REMARKS

When 6Al-4V titanium-alloy sheet is heated at temperature rates from 0.2° F to 100° F per second under constant-load condition, yield strength and rupture strength vary from less than to several times the corresponding yield strength and tensile strength obtained from elevated-temperature tensile stress-strain tests. The largest variation is obtained at high temperatures and temperature rates. Both yield temperatures and rupture temperatures increase linearly with the logarithm of the temperature rate, with the rupture temperature being the more sensitive to the increase in the temperature rate.

Yield and rupture strengths and temperatures under rapid-heating and constant-load conditions can be predicted by a master curve and a temperature-rate parameter. A phenomenological relation between stress, strain rate, and temperature can satisfactorily predict yield temperatures in the high temperature region. The constants used in the relation were determined from the tensile creep data.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 4, 1959.

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TABLE 1.- CHEMICAL COMPOSITION AND LONGITUDINAL TENSILE PROPERTIES OF 6Al-4V TITANIUM-ALLOY SHEET*

(a) Chemical composition

Element	Percent
Al	6.3
V	4.2
Fe	.11
C	.018
N_2	.012
H_2	.008

(b) Longitudinal tensile properties at room temperature

Yield strength, ksi	Tensile strength, ksi	Elongation in 2 inches, percent	Hardness, Rockwell A
164	174	8.5	70
164	175	9.5	70
162	173	10.5	69
163	174	10.0	69

*Information supplied by Boeing Airplane Company.

TABLE 2.- TENSILE STRESS-STRAIN PROPERTIES OF 6Al-4V TITANIUM-ALLOY SHEET FOR

1/2-HOUR EXPOSURE AND STRAIN RATE OF 0.002 PER MINUTE

Temperature, °F	Yield strength, ksi	Tensile strength, ksi	Young's modulus, ksi	Elongation in 2 inches, percent
80	152.9	168.0	16.0 × 10³	12
	152.1	167.9	16.0	12
	158.0	172.9	15.8	18
			[a]15.9	
	156.5	168.5	[b]17.4	10
	156.0	169.0	[b]17.2	9
200	142.0	158.0	15.1 × 10³	9
	142.0	161.0	14.7	12
			[c]15.0	
400	120.0	144.1	12.7 × 10³	12
	117.0	141.9	13.8	10
			[c]13.6	
600	108.0	134.0	13.6 × 10³	10
	107.0	133.0	13.5	9
			[c]12.7	
800	98.7	123.0	11.2 × 10³	12
	96.0	122.0	11.5	14
			[c]12.3	
1,000	60.0	71.0	8.1 × 10³	35
	59.0	69.0	11.6	32
	59.6	69.4	8.8	18
			[c]9.8	
1,200	19.8	25.9	6.9 × 10³	82
	23.2	25.1	6.7	102
	----	23.0	---------	42
	----	24.6	---------	42

[a]Loaded in elastic region only; strain measured with Tuckerman strain gages.

[b]Specimen loaded cross grain.

[c]Loaded in elastic region only.

TABLE 3.- TENSILE PROPERTIES OF 6Al-4V TITANIUM-ALLOY SHEET

UNDER RAPID-HEATING CONDITIONS

Stress, ksi	Temperature rate, $^{\circ}$F/sec	Yield temperature, $^{\circ}$F	Rupture temperature, $^{\circ}$F	Elongation in 2 inches, percent
25	0.2	1,080	(a)	
	2	1,075	1,270	26
	2	1,185	1,420	49
	2	1,205	(a)	
	20	1,340	1,660	41
	20	1,340	(a)	
	20	1,235	(a)	
	60	1,245	1,640	41
	100	1,325	1,610	40
50	0.2	985	1,150	20
	2	1,105	1,265	27
	20	1,190	1,420	29
	20	1,195	1,400	27
	100	1,235	1,450	27
75	0.2	835	1,040	19
	.2	820	970	18
	.2	890	1,070	22
	2	945	1,115	16
	20	1,030	1,260	19
	95	1,085	1,330	16
100	0.2	595	960	14
	.2	680	(b)	
	2	685	1,050	14
	20	710	1,090	12
	20	700	1,185	12
	72	755	1,120	11
	94	795	1,155	12

[a]No rupture; specimen elongated to limits of machine.

[b]Temperature rate increased sharply after specimen passed yield point.

TABLE 4.- AVERAGE COEFFICIENTS OF THERMAL EXPANSION

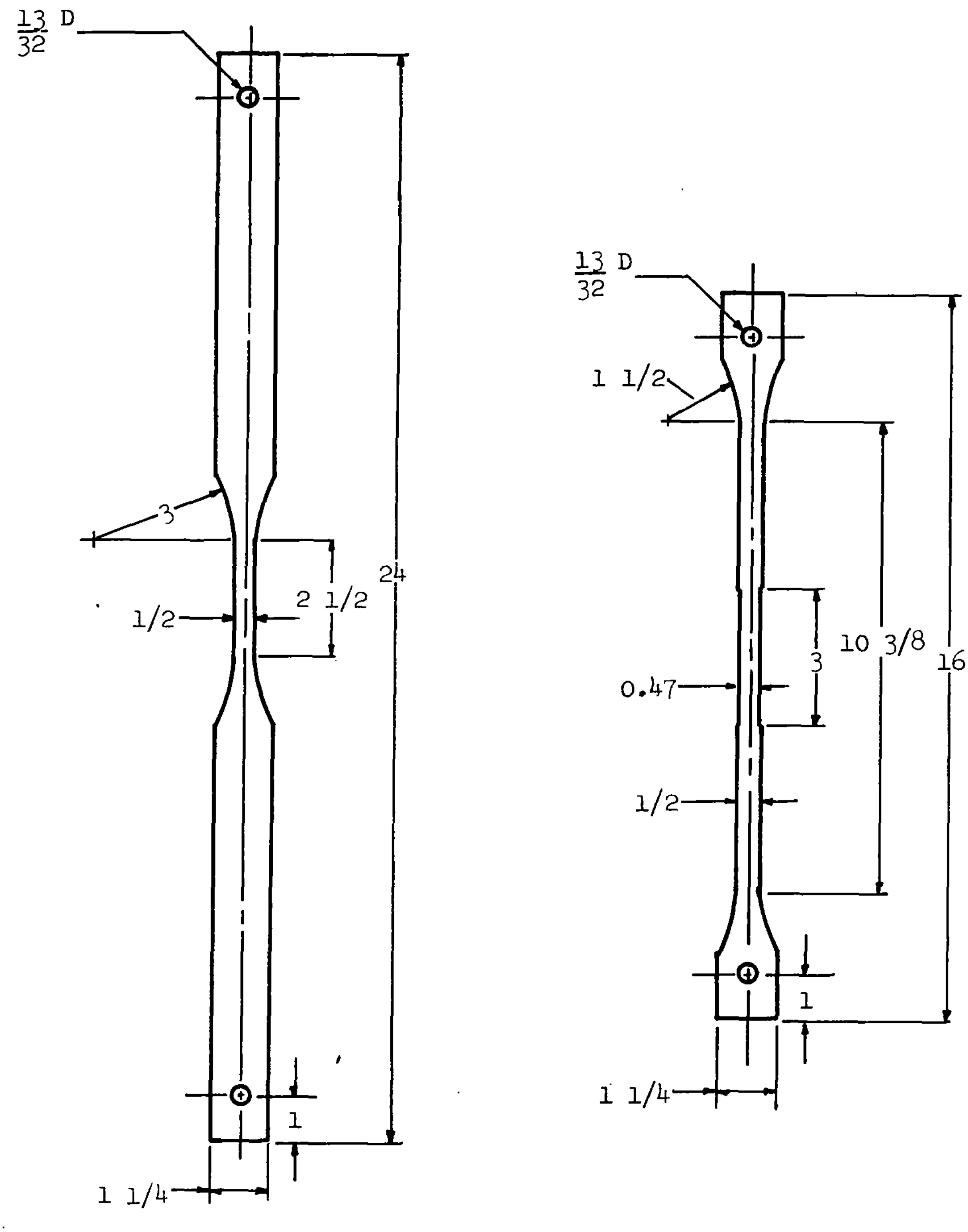
OF 6Al-4V TITANIUM-ALLOY SHEET

Temperature range, °F	Thermal strain	Average coefficient of linear thermal expansion, per °F
80 to 200	0.0006	5.0×10^{-6}
80 to 400	.0018	5.6
80 to 600	.0029	5.6
80 to 800	.0040	5.6
80 to 1,000	.0052	5.7
80 to 1,200	.0065	5.8
80 to 1,400	.0081	6.1
80 to 1,600	.0097	6.4
80 to 1,800	.0116	6.7

TABLE 5.- TENSILE CREEP PROPERTIES OF 6Al-4V TITANIUM-ALLOY SHEET

Temperature, °F	Stress, ksi	Minimum creep rate per hr	Number of hours to a creep strain of -			Time to rupture, hr
			0.2 percent	0.5 percent	1.0 percent	
800	90	0.00174	0.255	1.07	3.45	(a)
	85	.000896	.365	1.65	5.1	51.7
	80	.000644	.59	3.0	9.6	84.8
	75	.000261	.64	5.6	21.0	256.7
1,000	60	0.0513	0.032	0.080	0.18	1.8
	55	.0321	.043	.13	.305	(a)
	45	.0101	.083	.32	.79	24.7
	40	.00765	.125	.78	1.55	25.3
	30	.00128	.42	1.9	5.6	116.1

[a]No rupture time obtained.



(a) Stress strain and creep.

(b) Rapid heating.

Figure 1.- Stress-strain, creep, and rapid-heating tensile test specimens. All dimensions are in inches.

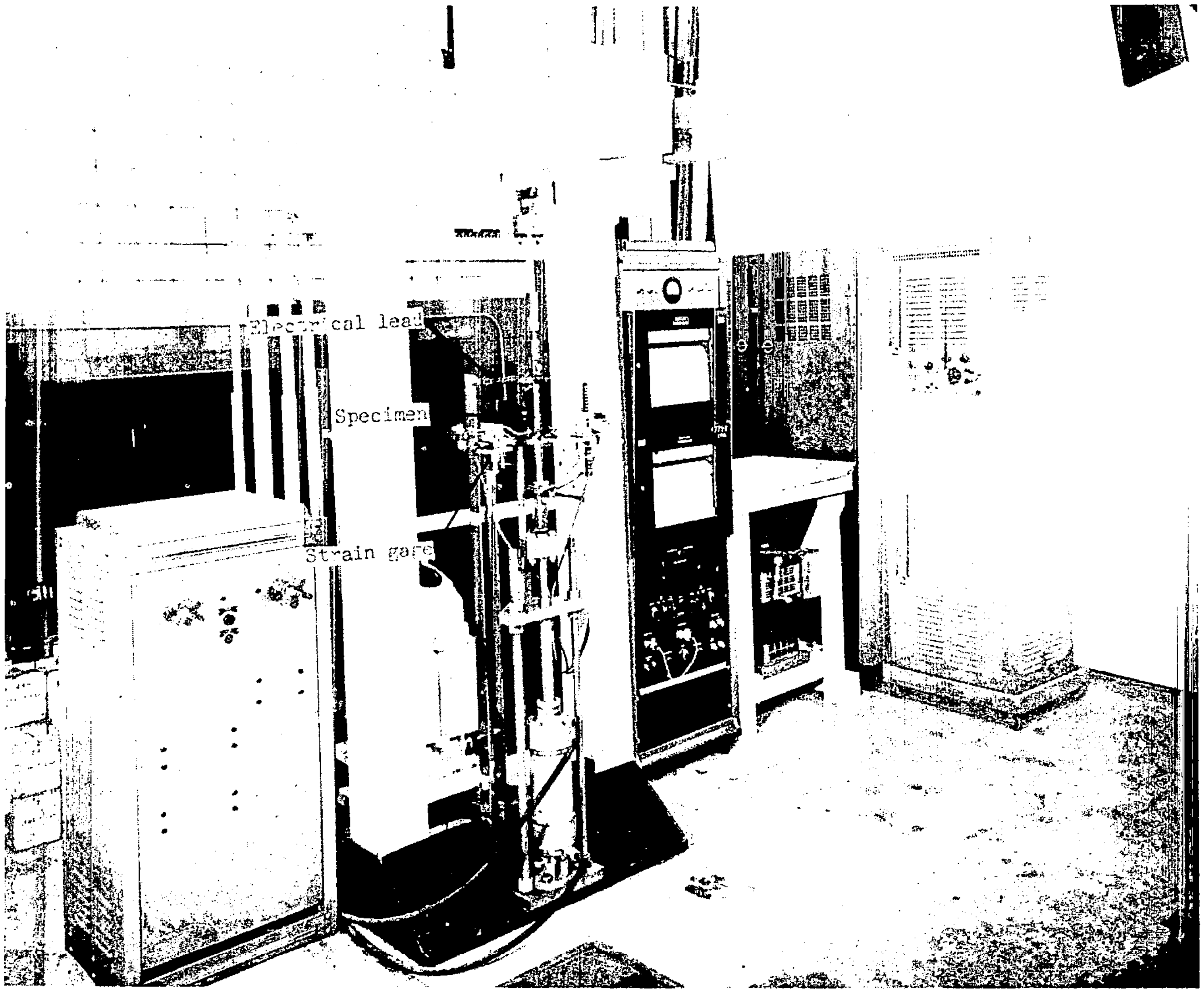


Figure 2.- Rapid-heating equipment. L-57-2302.1

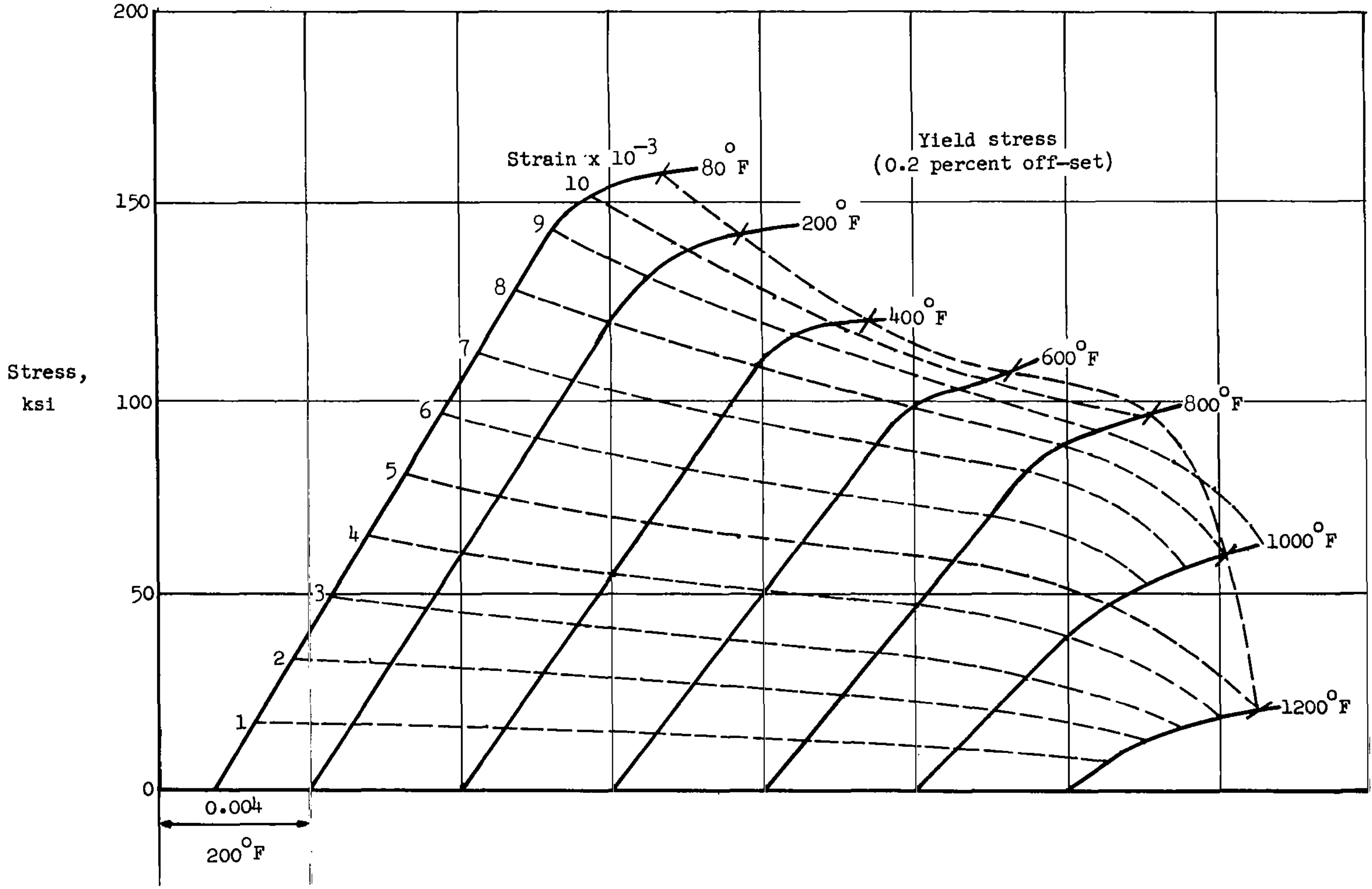


Figure 3.- Elevated-temperature tensile stress-strain curves for 6Al-4V titanium-alloy sheet after 1/2-hour exposure for a strain rate of 0.002 per minute.

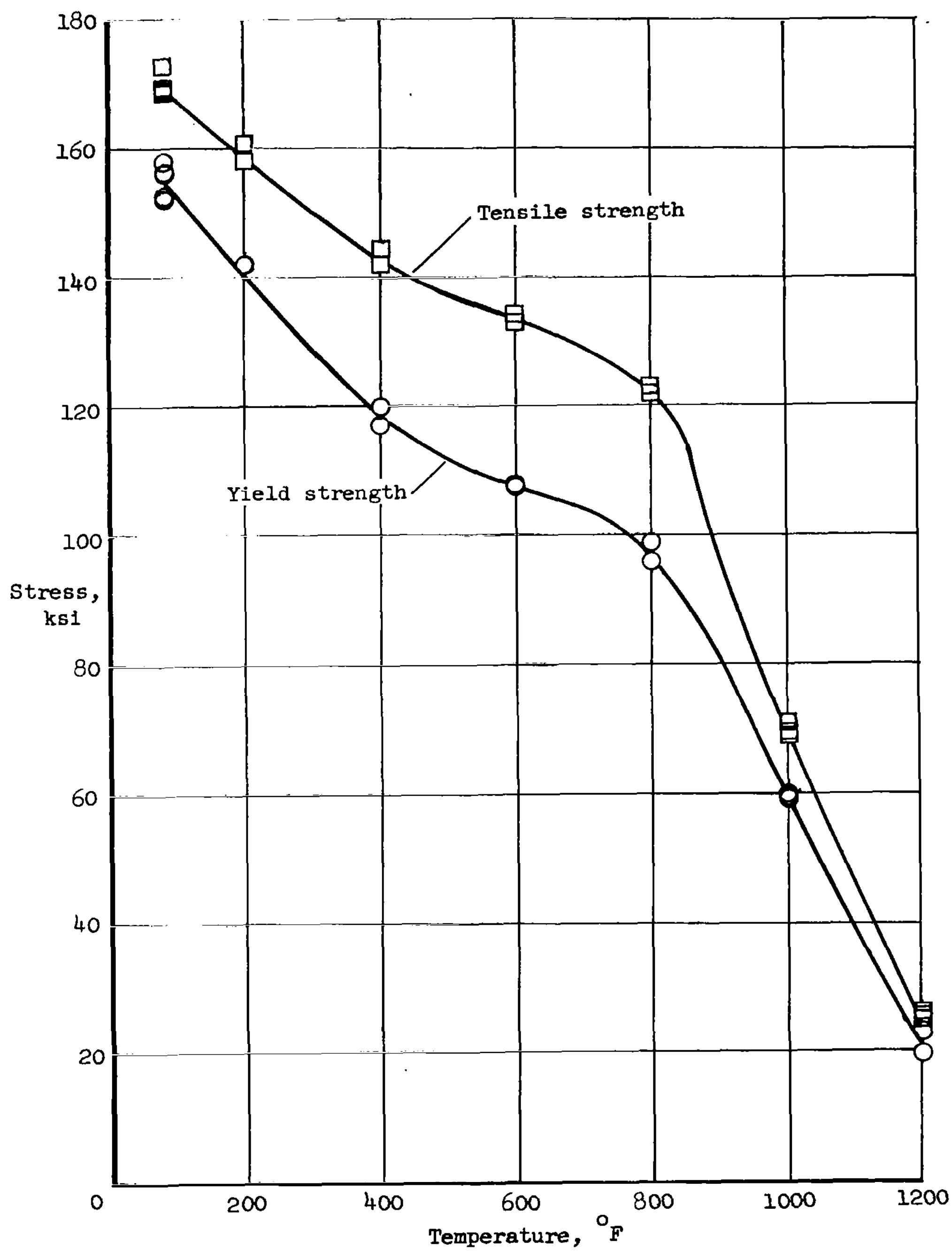


Figure 4.- Yield strength and tensile strength for 6Al-4V titanium-alloy sheet at elevated temperatures after 1/2-hour exposure for a strain rate of 0.002 per minute.

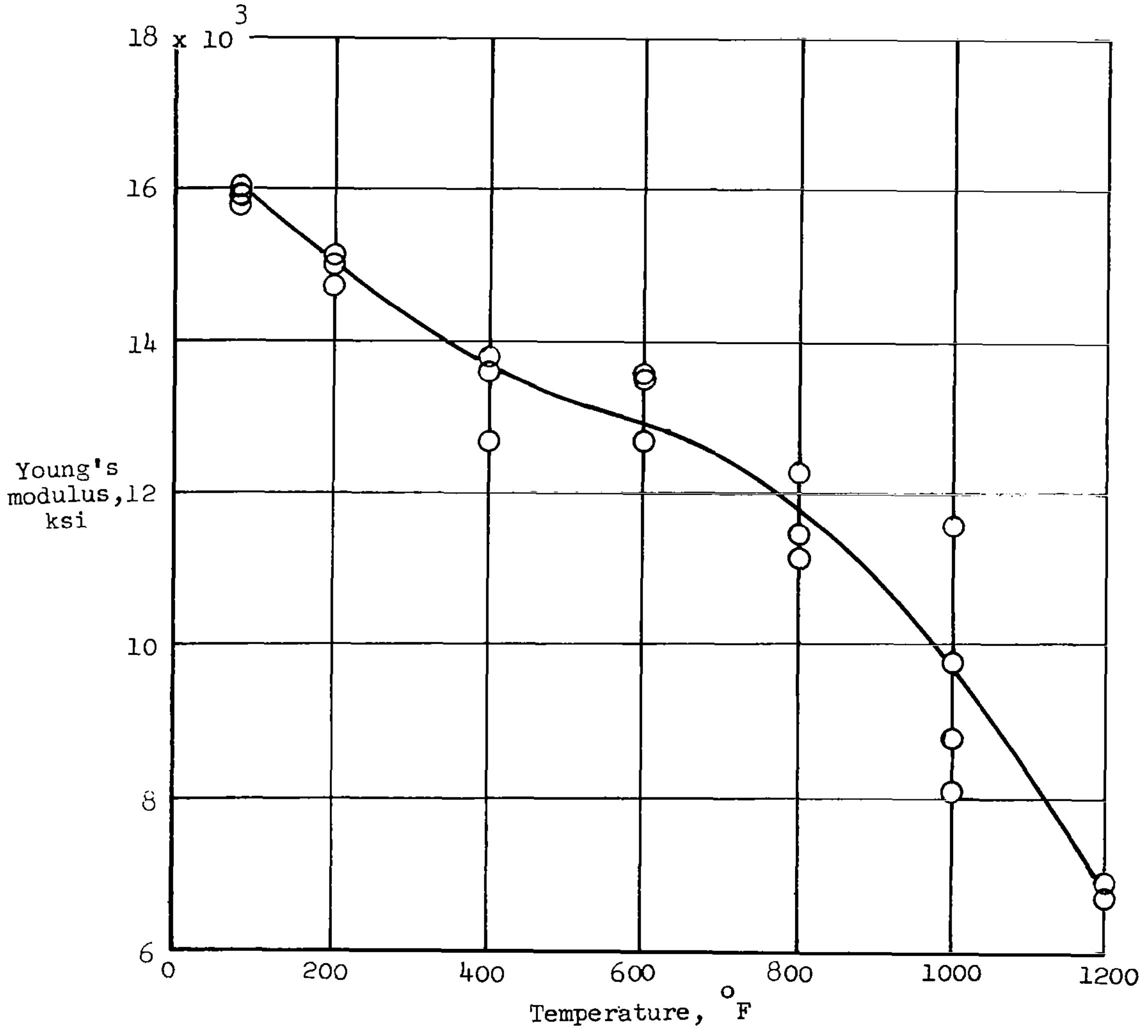


Figure 5.- Young's modulus for 6Al-4V titanium-alloy sheet after 1/2-hour exposure at elevated temperatures.

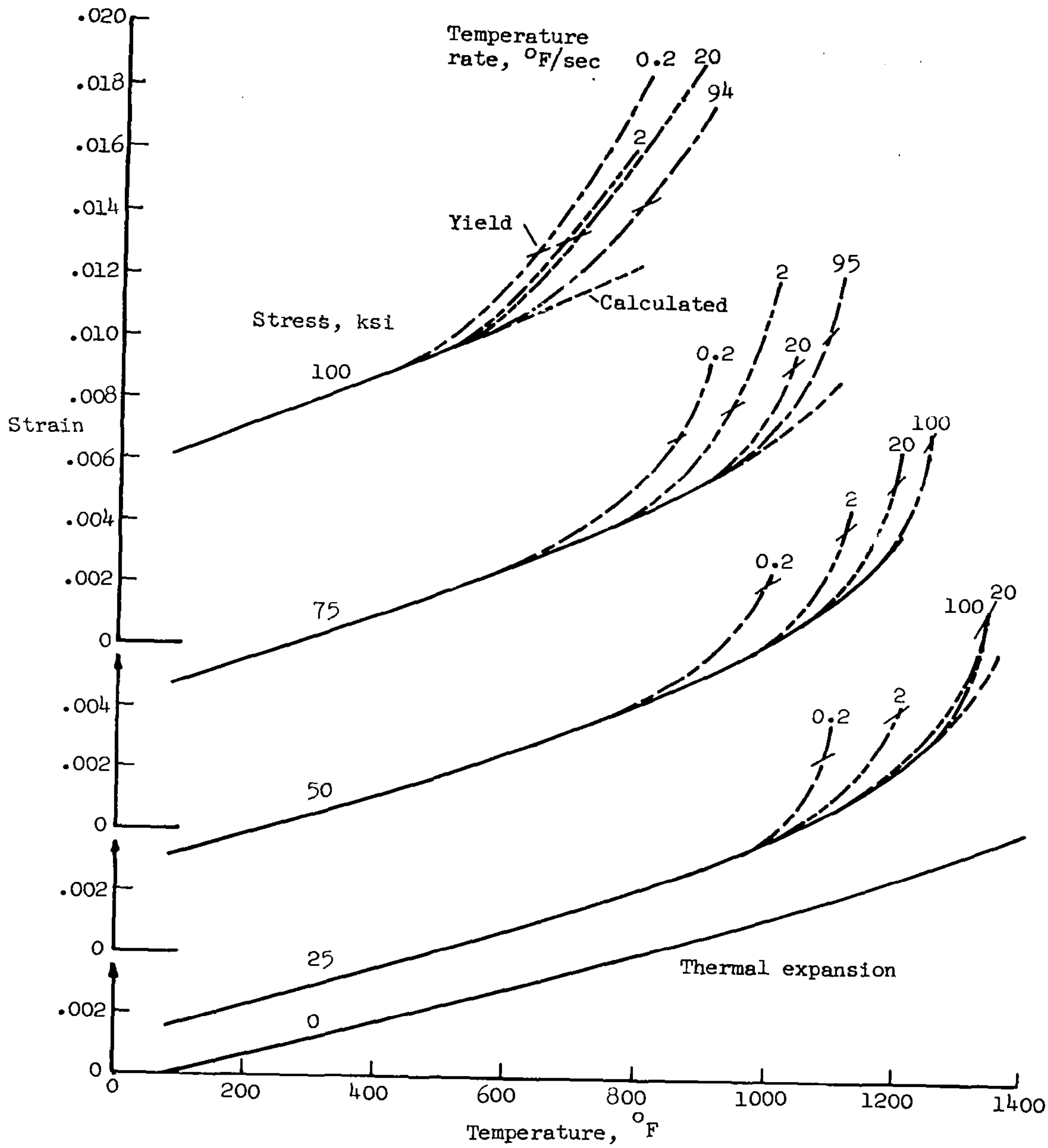
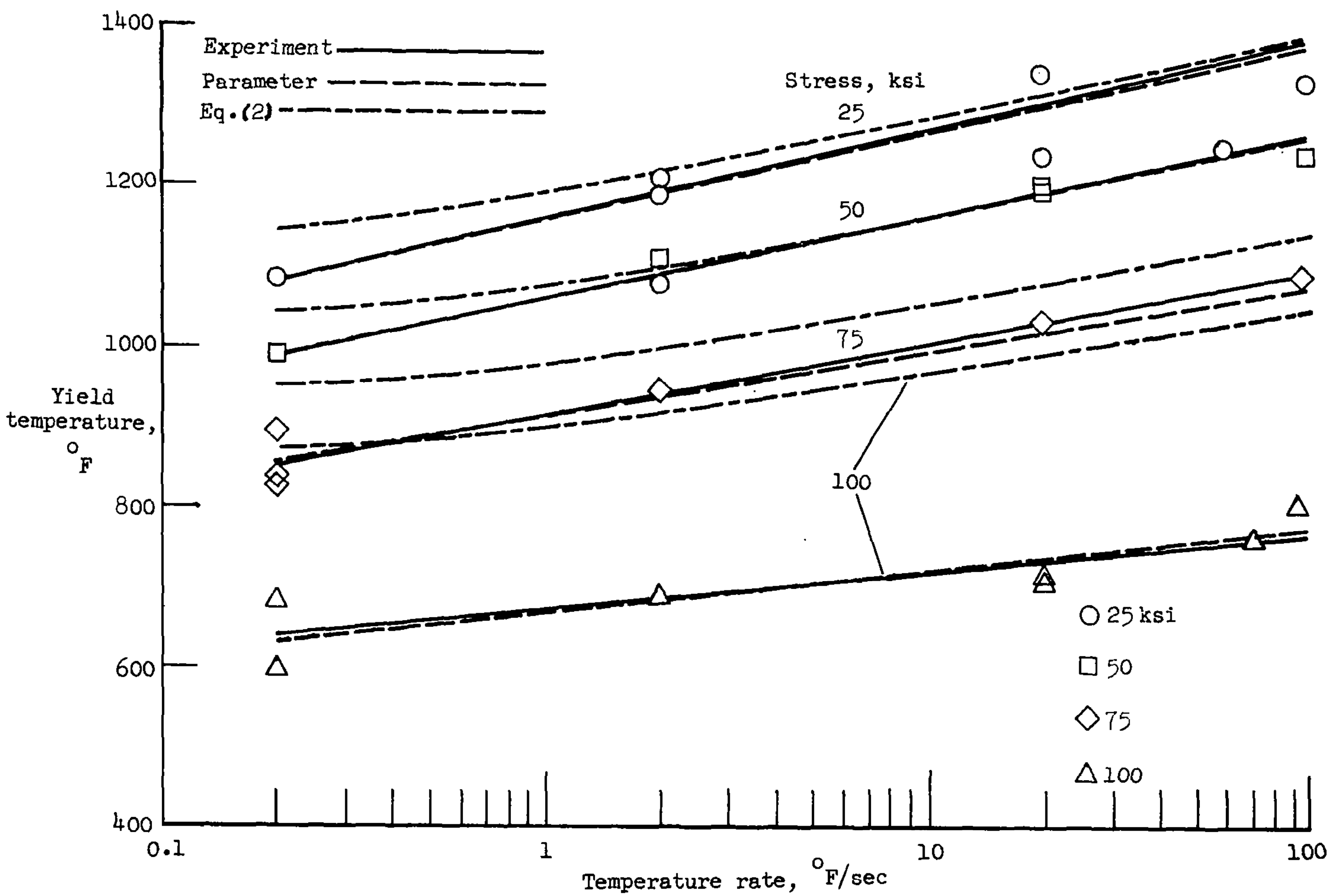
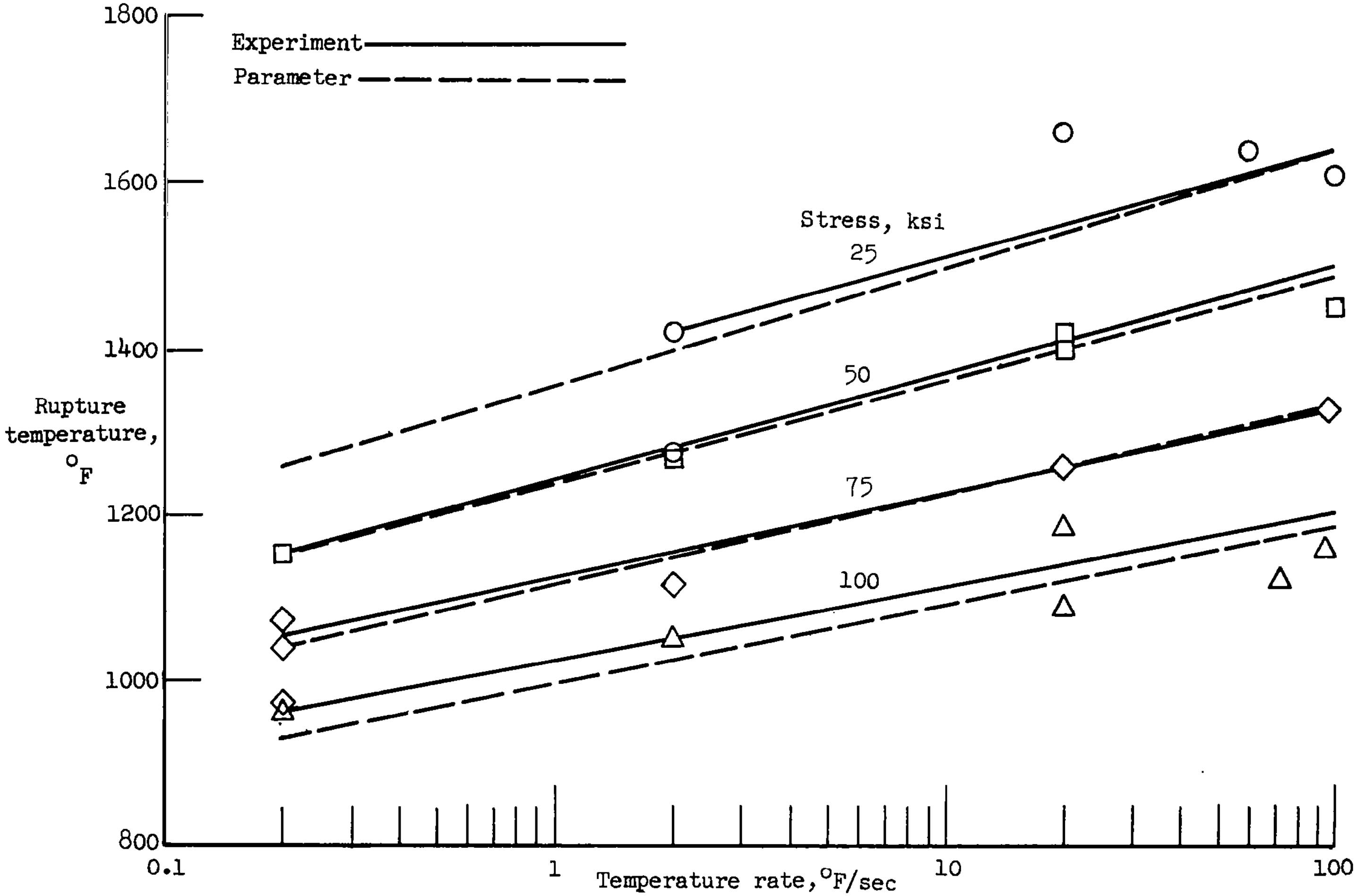


Figure 6.- Strain-temperature histories for 6Al-4V titanium-alloy sheet for temperature rates from 0.2° F to 100° F per second.



(a) Yield.

Figure 7.- Experimental and calculated yield and rupture temperatures for 6Al-4V titanium-alloy sheet for temperature rates from 0.2° F to 100° F at four stresses.



(b) Rupture.

Figure 7.- Concluded.

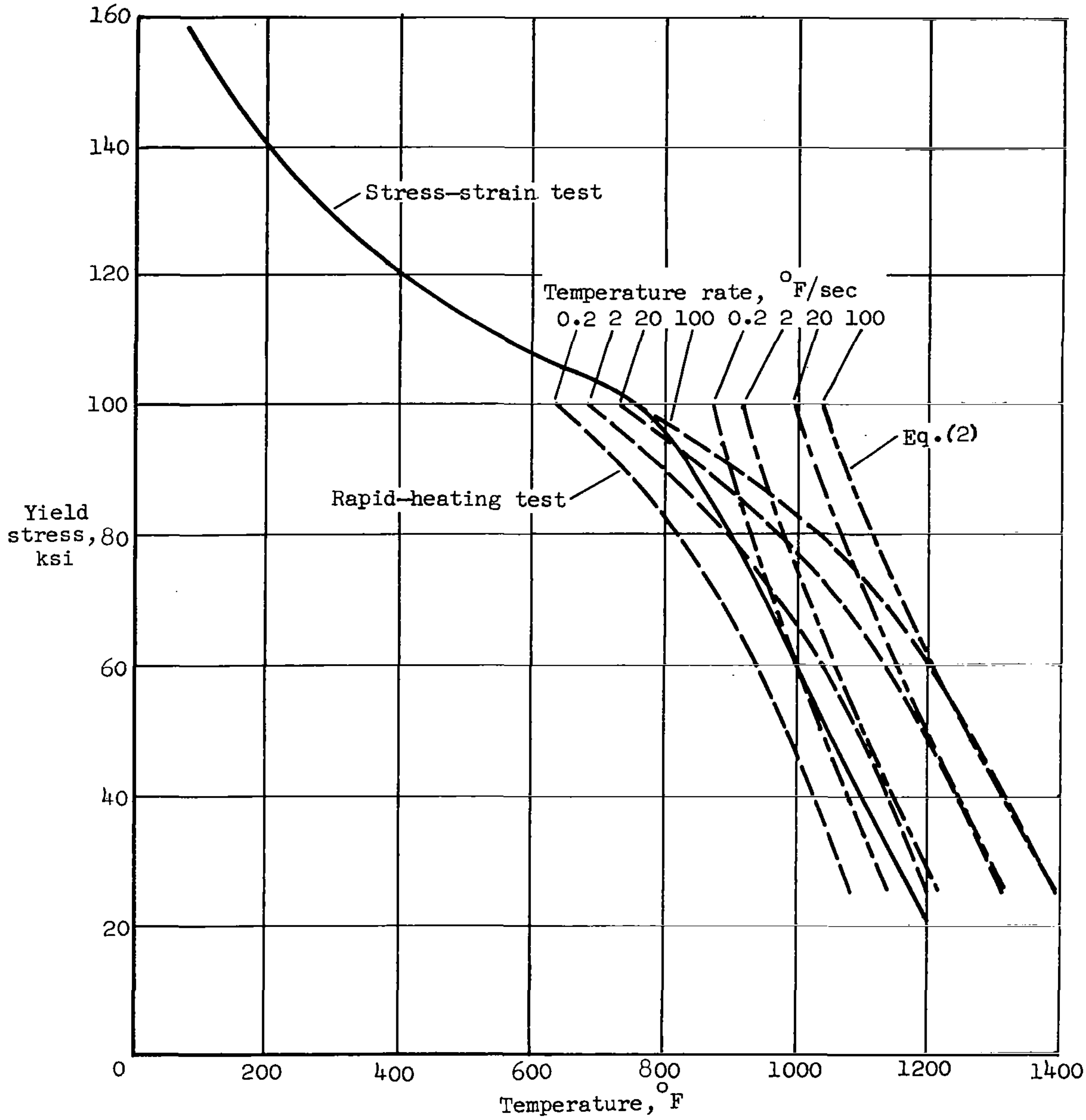


Figure 8.- Tensile yield strength of 6Al-4V titanium-alloy sheet for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute, for rapid-heating tests from 0.2° F to 100° F per second, and as calculated by equation (2).

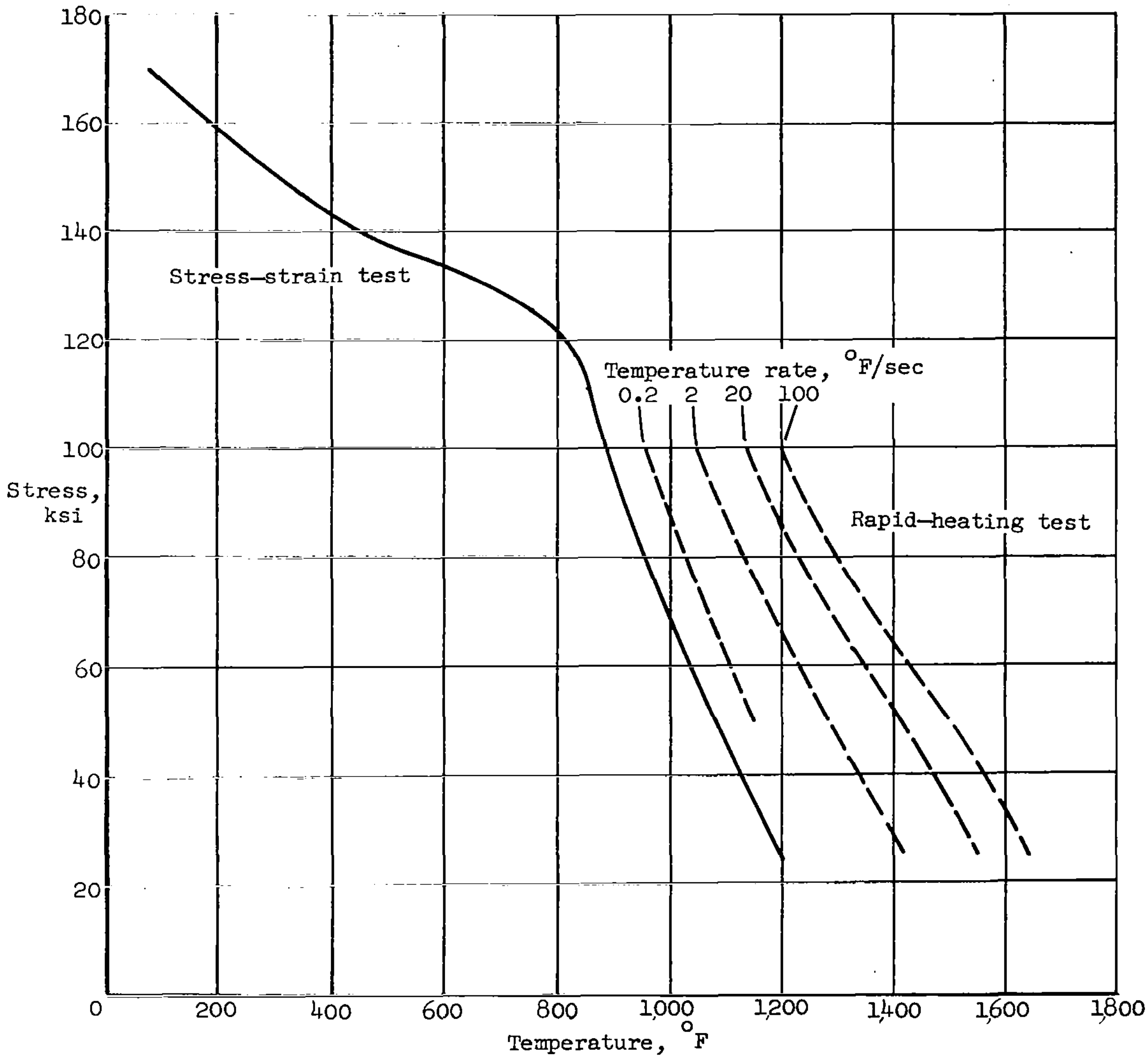
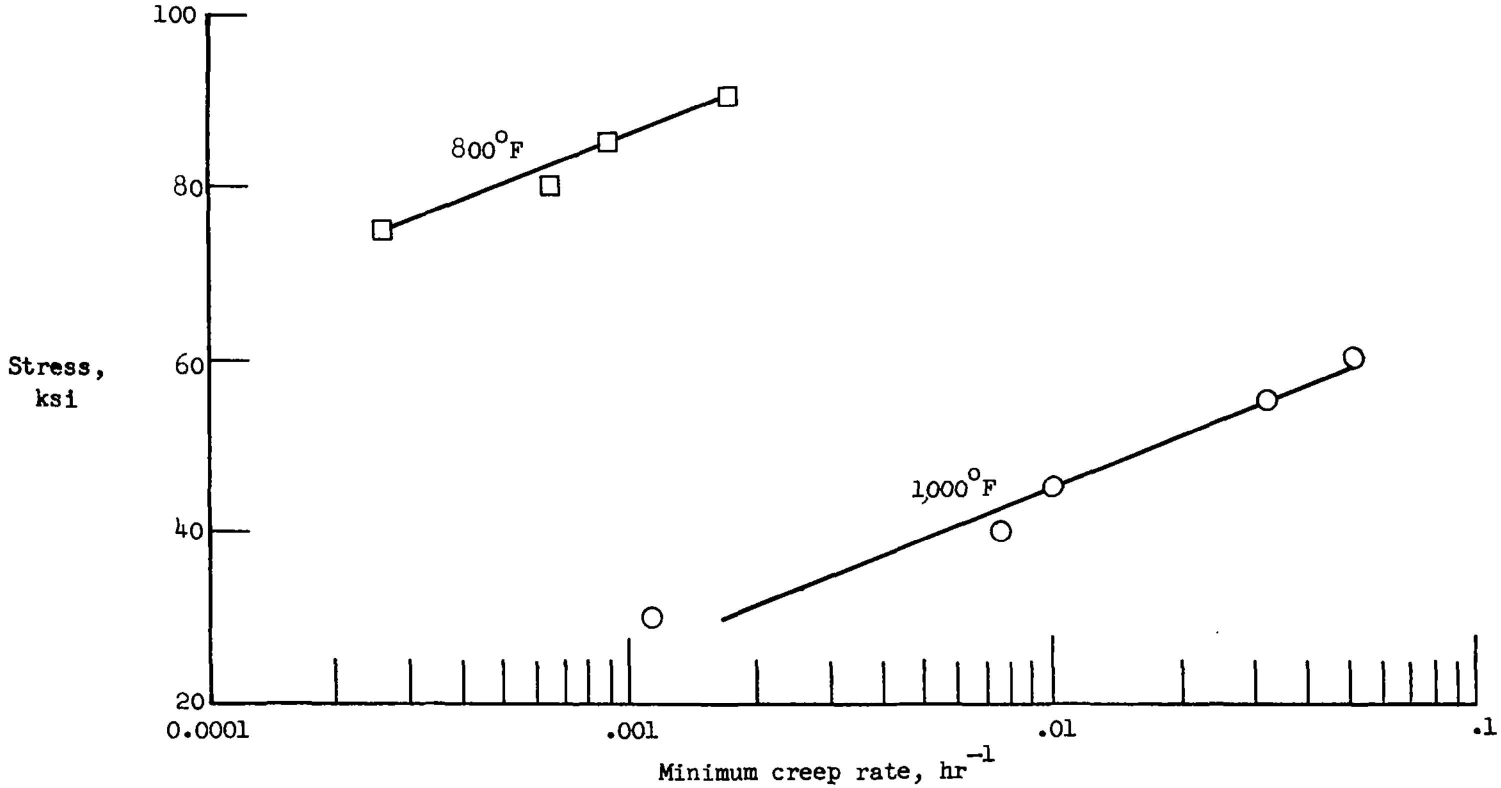
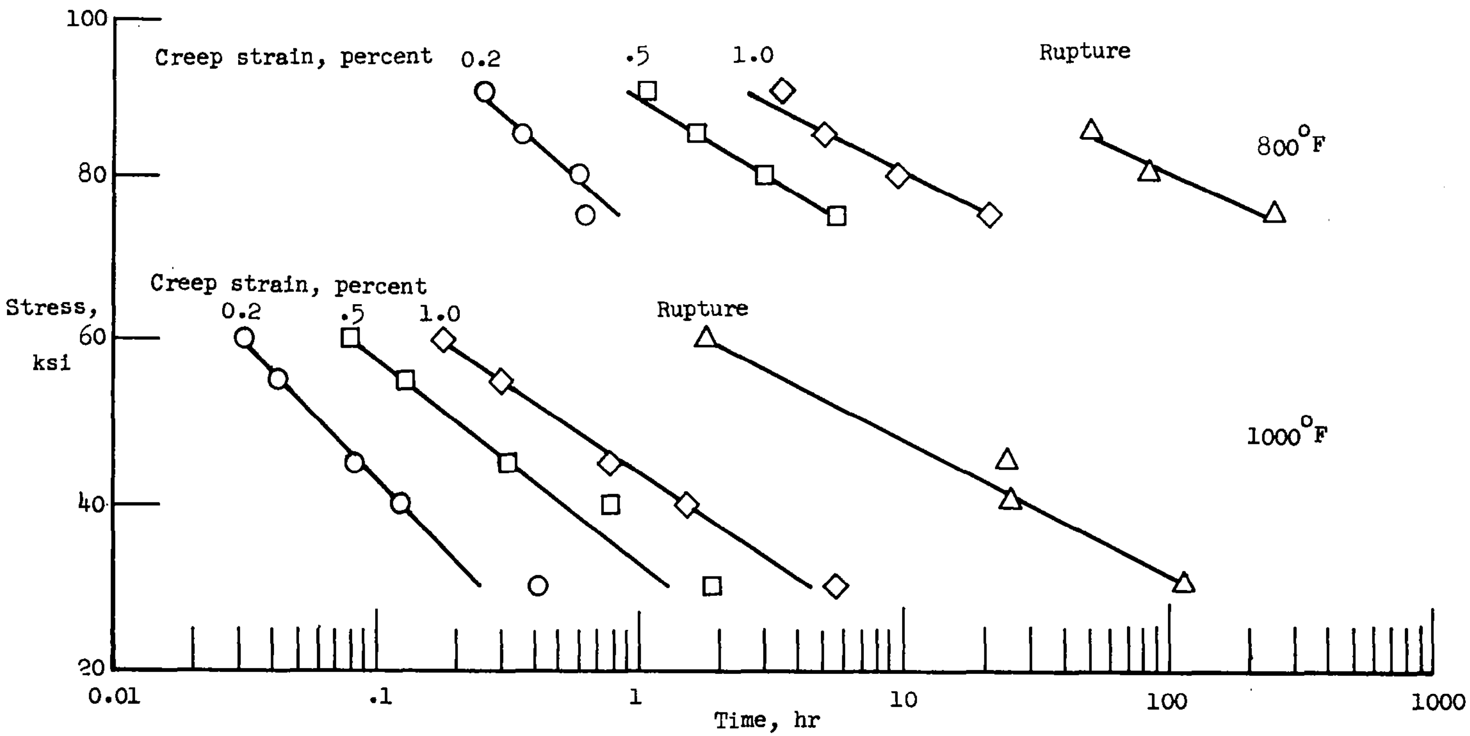


Figure 9.- Tensile strength of 6Al-4V titanium-alloy sheet for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute and for rapid-heating tests from 0.2° F to 100° F per second.



(a) Minimum creep rate.

Figure 10.- Minimum creep rate and time to a given creep strain at 800° F and 1,000° F for 6Al-4V titanium-alloy sheet under constant-temperature—constant-tensile-load conditions.



(b) Time to a given creep strain.

Figure 10.- Concluded.

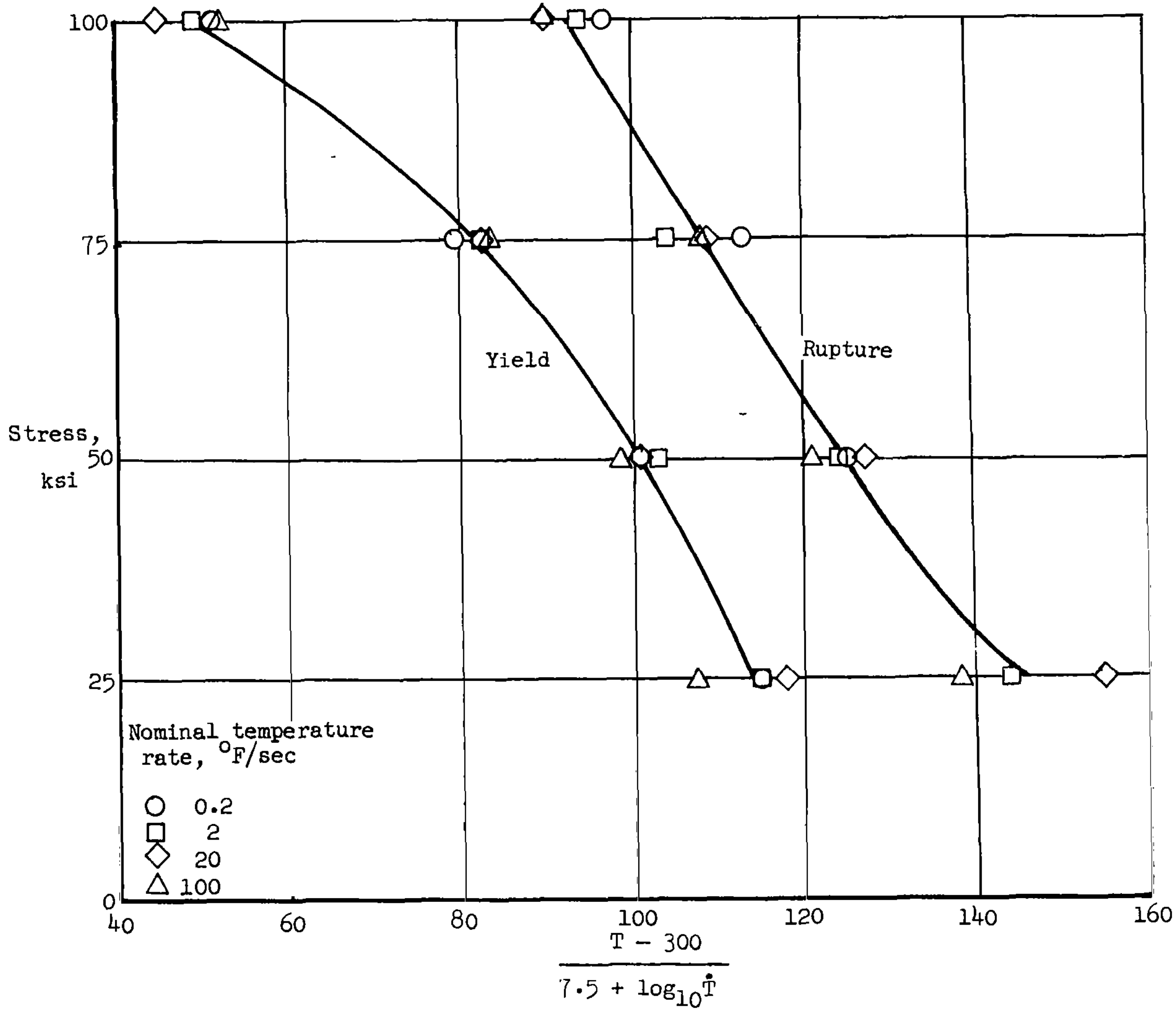


Figure 11.- Master yield- and rupture-stress curves for 6Al-4V titanium-alloy sheet using the temperature-rate parameter. T is in $^{\circ}F$ and $\dot{T}$ is in $^{\circ}F$ per second.

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